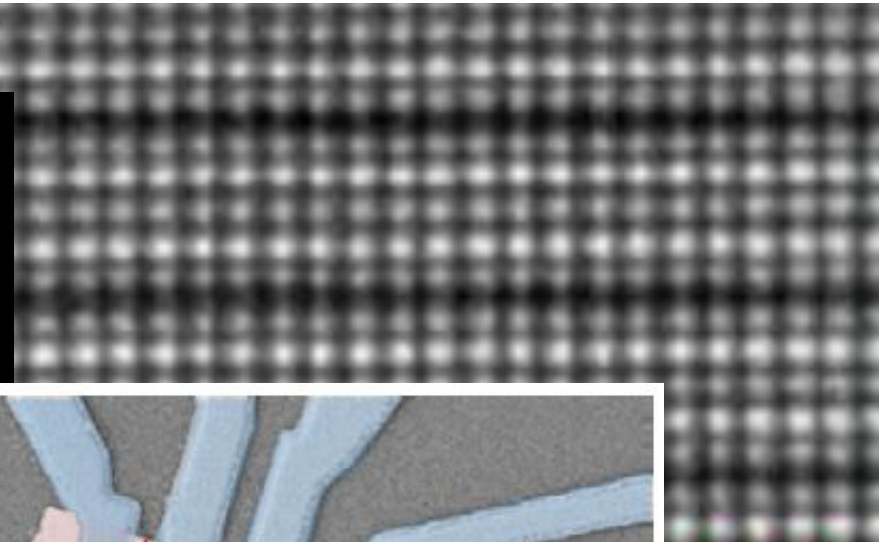
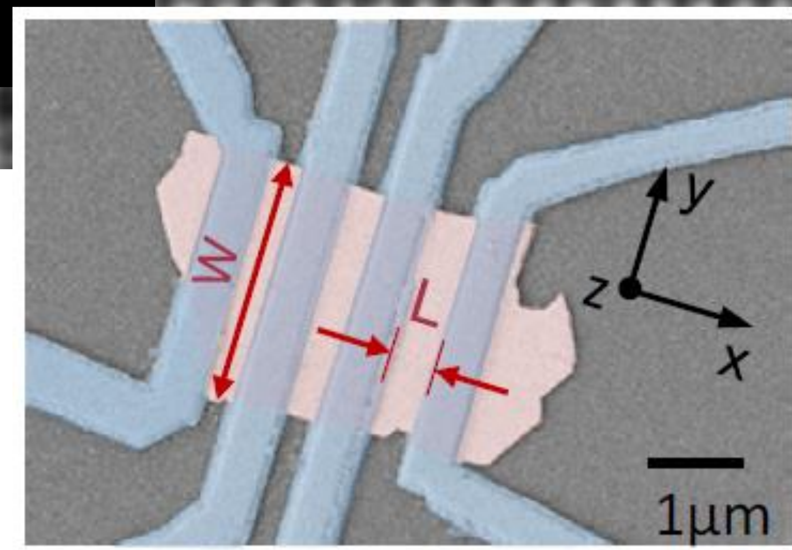
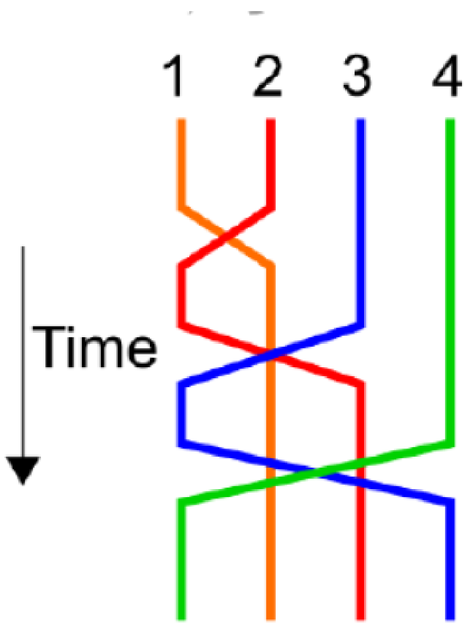


Bismuth based topological Josephson junctions

Alexander Brinkman

University of Twente, the Netherlands





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INSTITUTE FOR NANOTECHNOLOGY

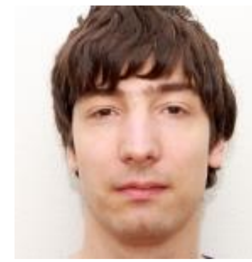
Acknowledgements

University of Twente

Chuan
Li

Jorrit
de Boer

Bob
de Ronde



Martijn
Lankhorst

University of Amsterdam

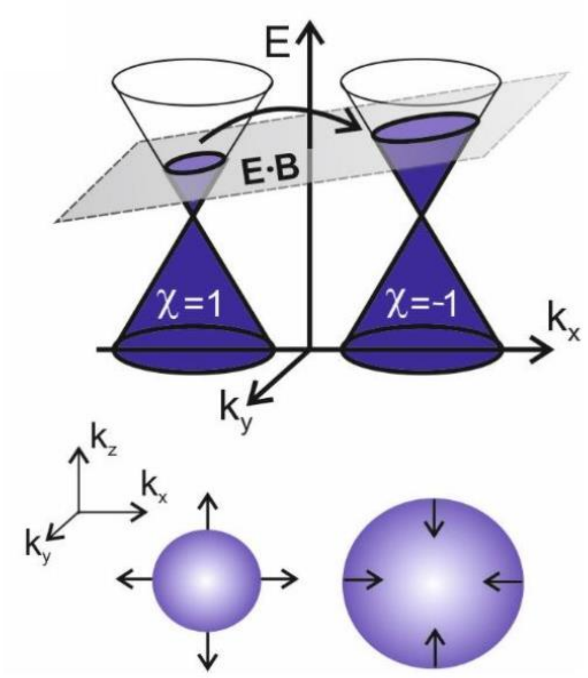
Yingkai Huang
Anne de Visser
Erik van Heumen
Mark Golden

Forschungszentrum Jülich

Peter Schüffelgen
Daniel Rosenbach
Thomas Schäpers
Detlef Grüzmacher

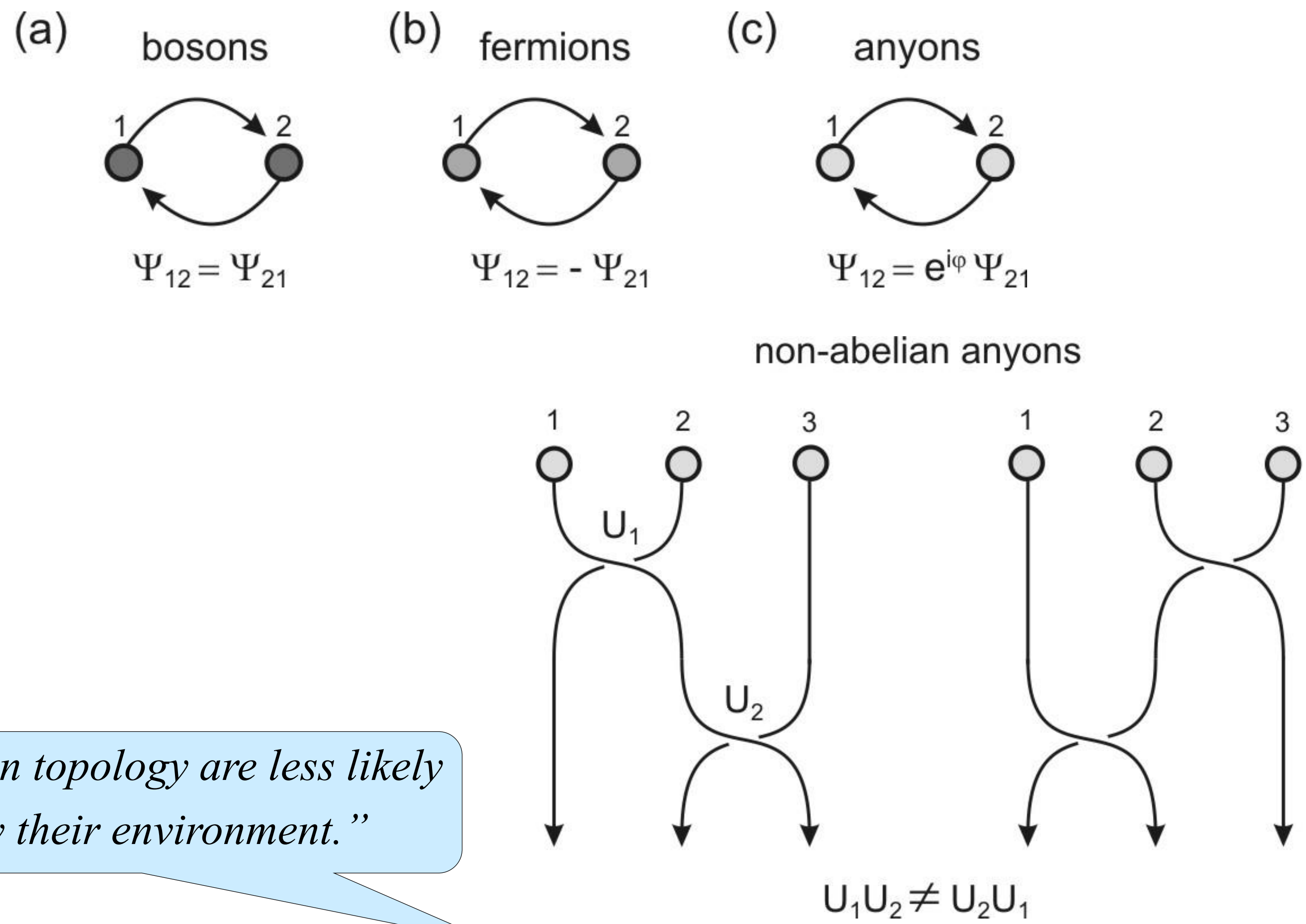
Message of this talk

3D helical **spin-momentum locking** of Dirac semimetal



- Topological transport
- 4π-periodic Andreev bound states
- Zeeman induced π-junction

Non-Abelian anyons

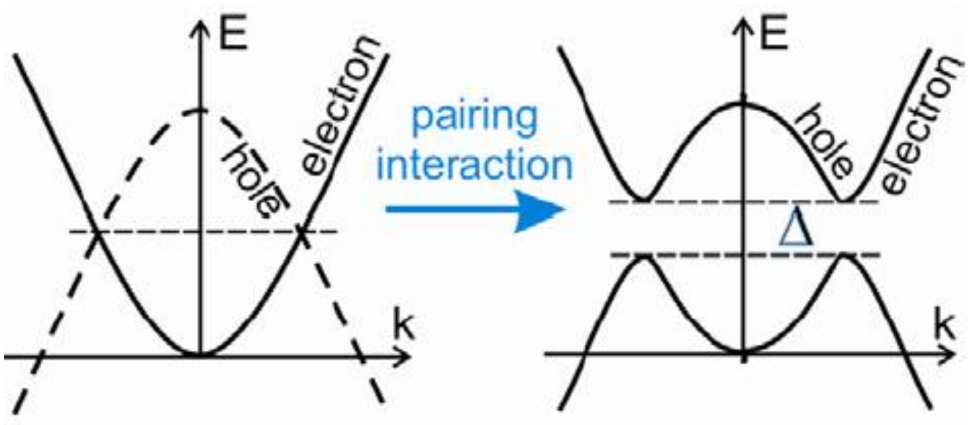


"Qubits stored in topology are less likely to be affected by their environment."

Microsoft

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), November 2019.
Invited presentation 3-EO-TS-02I given at EUCAS, 1 – 5 September 2019, Glasgow, UK.

Majoranas in superconductors?

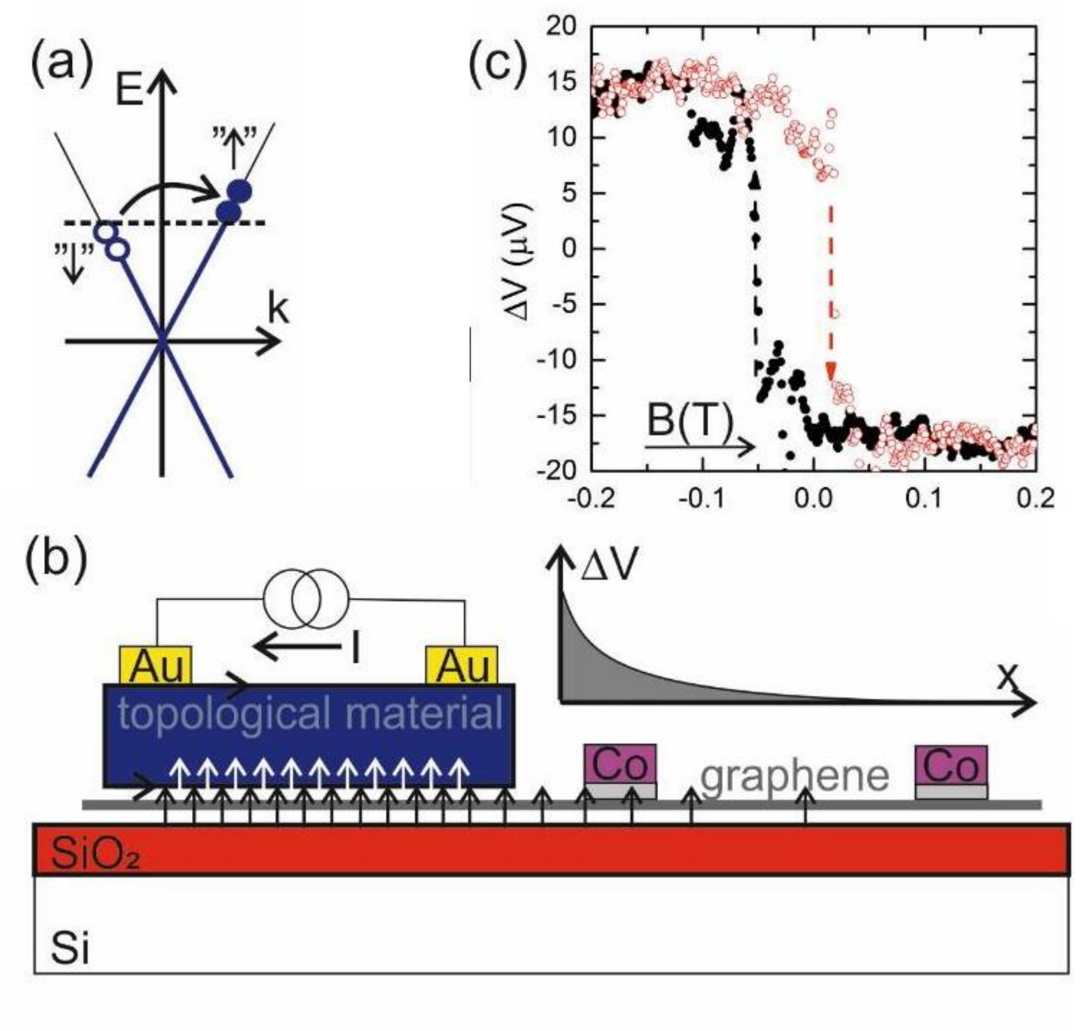


Bogoliubov quasiparticles: $\gamma_\epsilon = \gamma^\dagger_{-\epsilon}$

Needed for Majorana: $\gamma_\epsilon = \gamma^\dagger_\epsilon$

➔ Zero energy state required

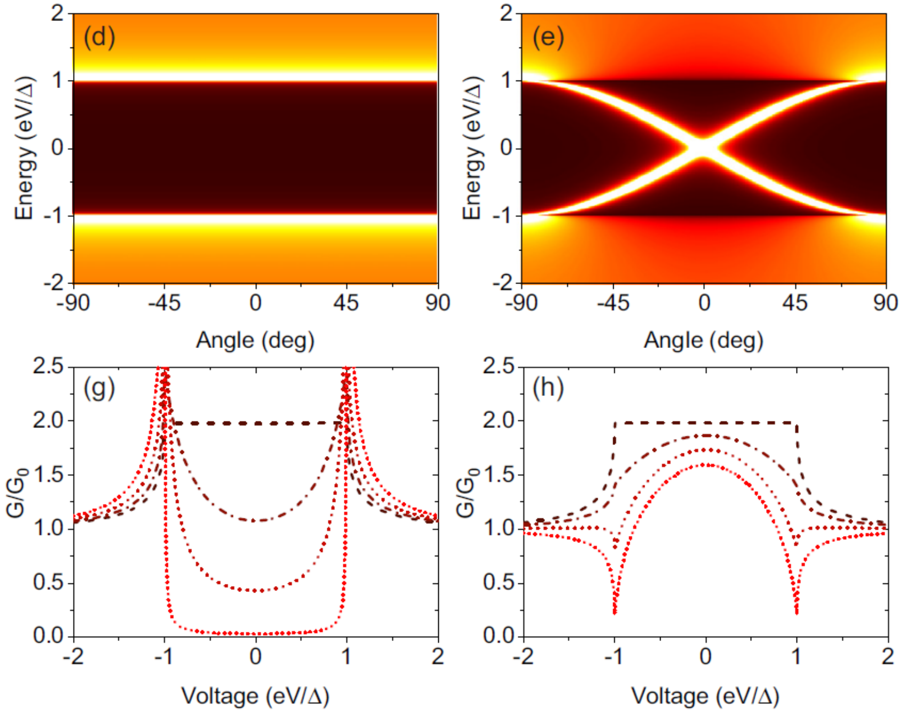
Spin-momentum locking



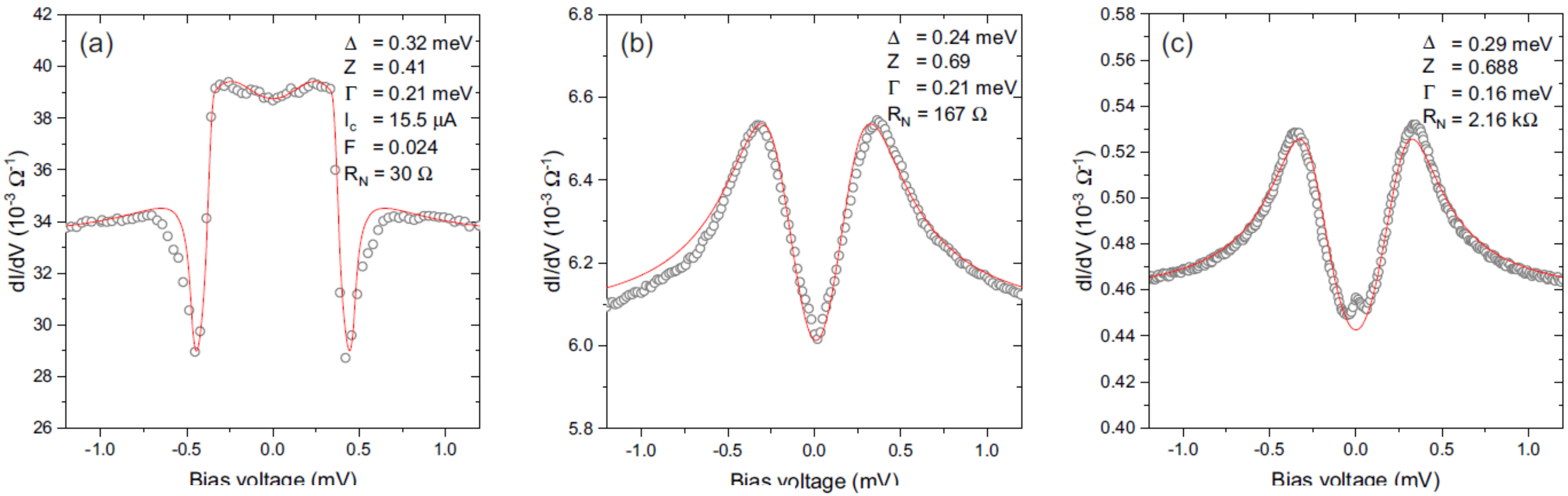
Adv. Electr. Mater. 201900334 (2019)

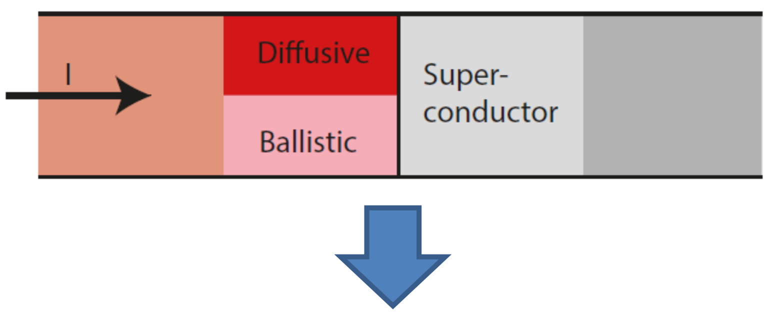
Topology and superconductivity

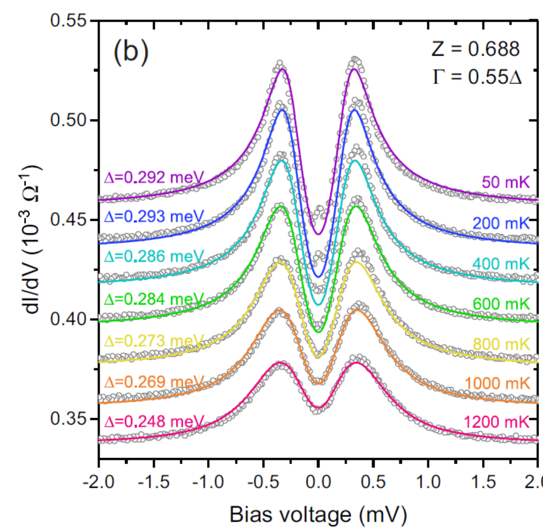
3D *s*-wave: 3D chiral *p*:



$PdTe_2$ type II Dirac semimetal







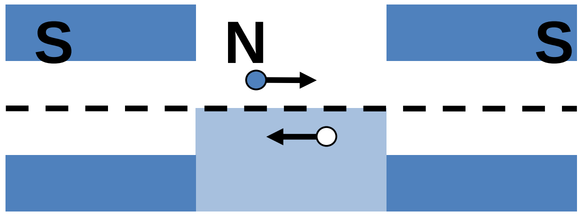
Dominant s-wave superconductor…

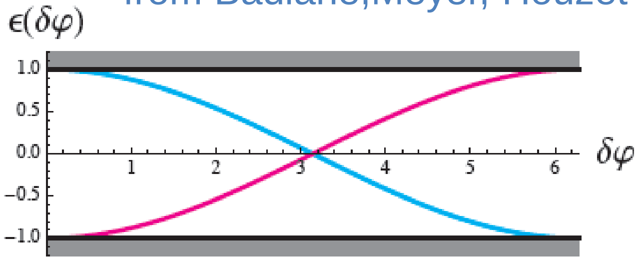
Phys. Rev. B **99**, 014510 (2019)

Why topological Josephson junctions?

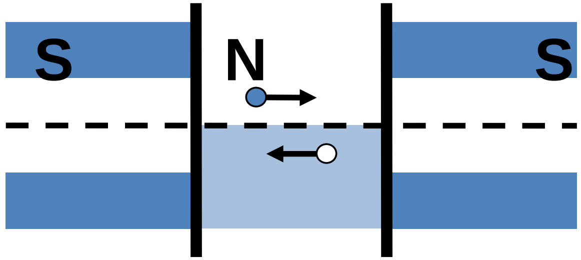
Calculations and figure from Badiane,Meyer, Houzet

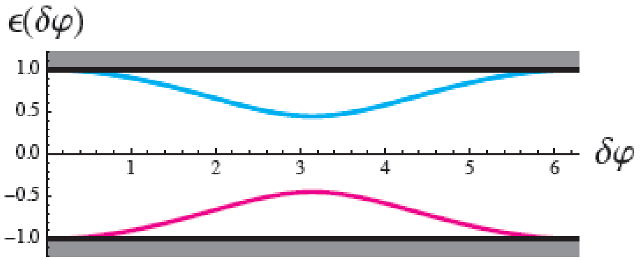
Standard SNS:



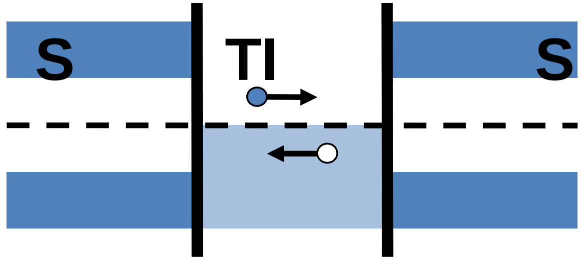


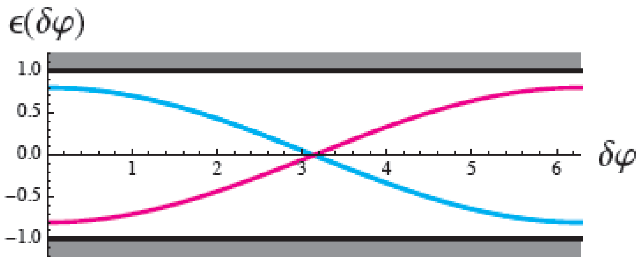
Including interface barrier:





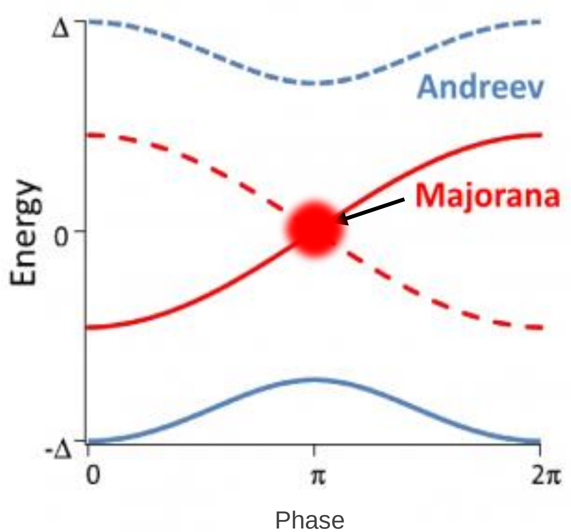
With topological interlayer:

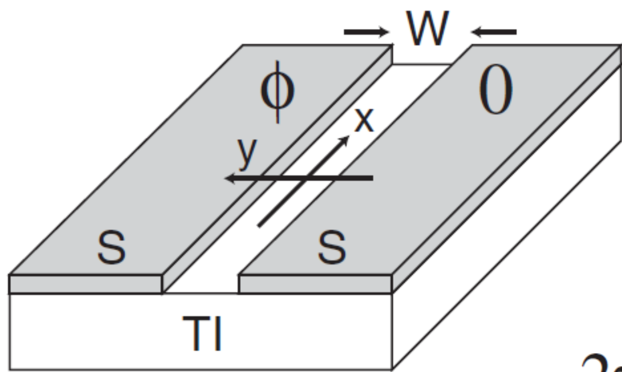


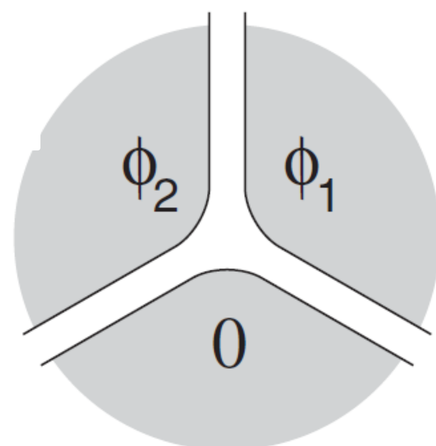


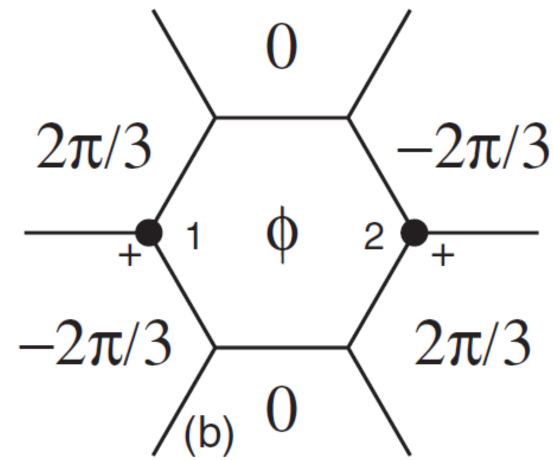
Majorana manipulation on a surface

Fu & Kane, PRL **100**, 096407 (2008)





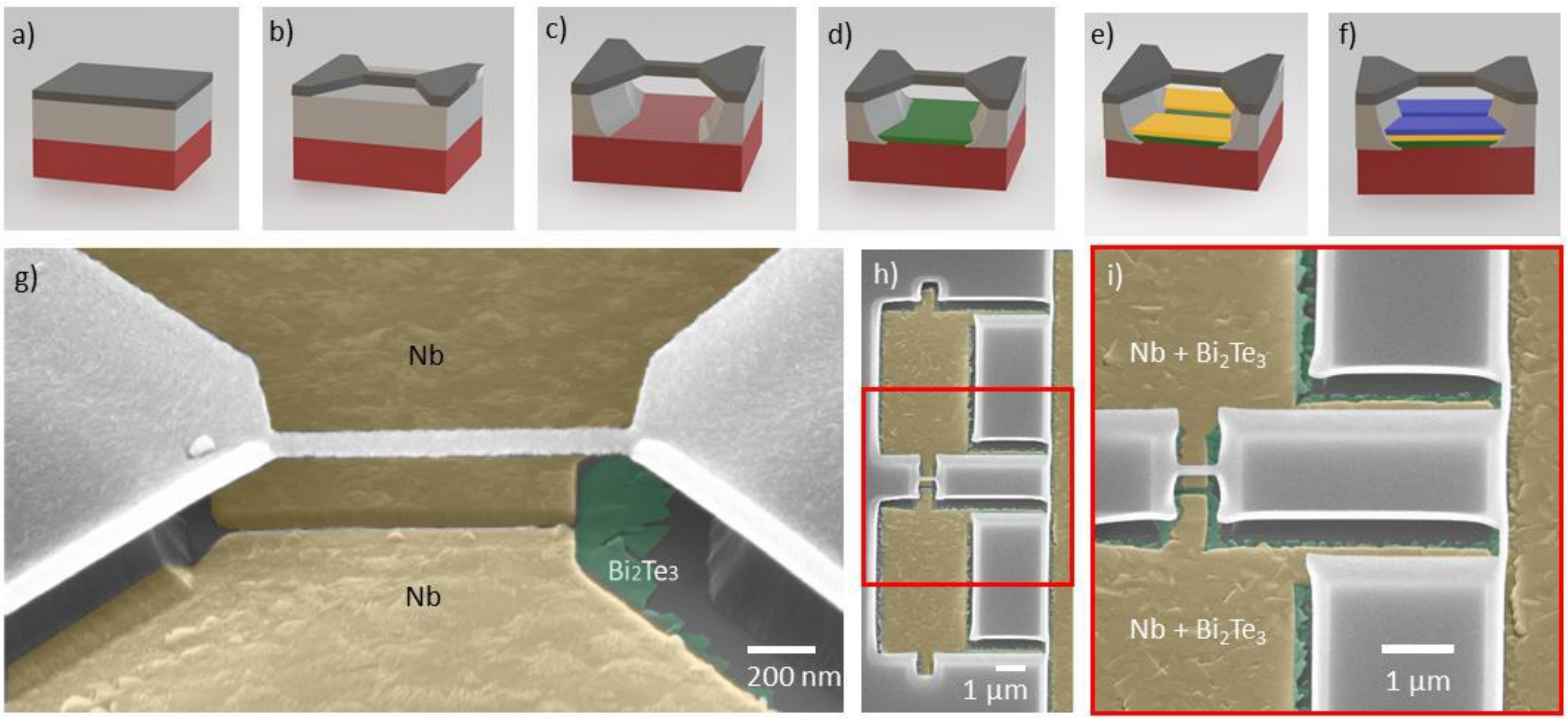




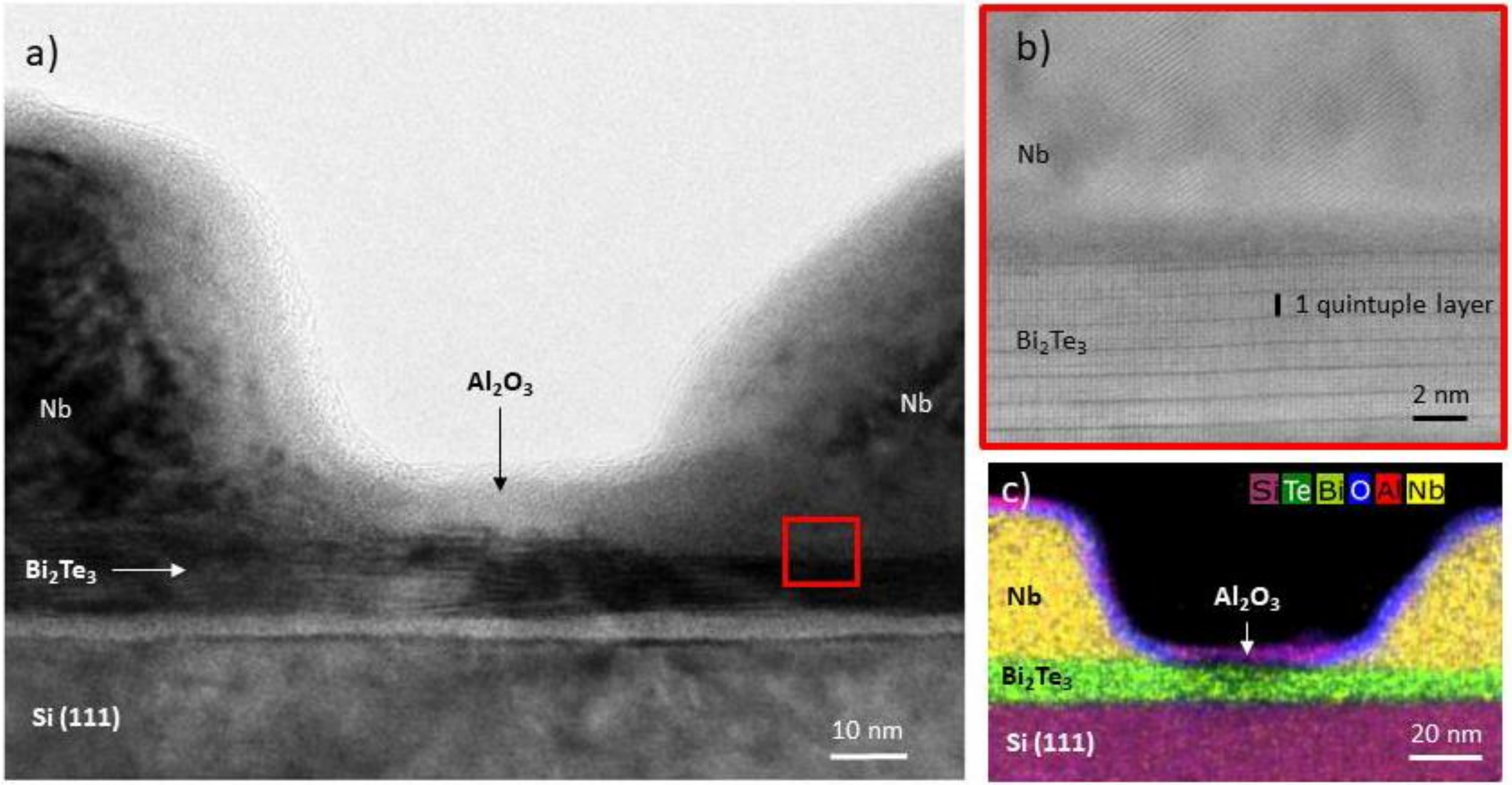
Advanced device fabrication

In situ electrode deposition by shadow mask technology → enhanced IcRn

Selective area growth → towards 1D



Advanced device fabrication

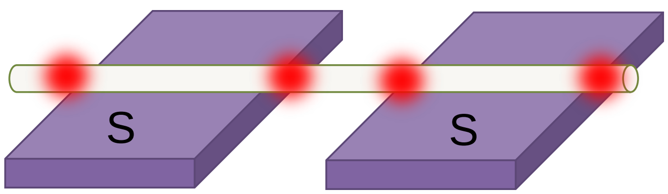


Nature Nanotechnology **14**, 821 (2019)

Majoranas

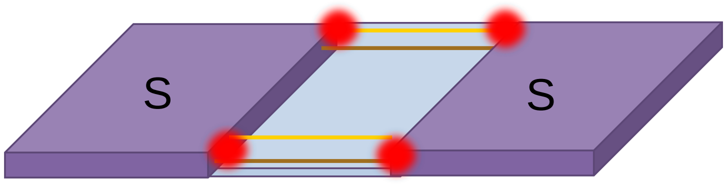
1D Nanowires (InAs, InSb…)

Strong evidence (Delft, Lund, Copenhagen)



1D edges of 2D QSH (HgTe)

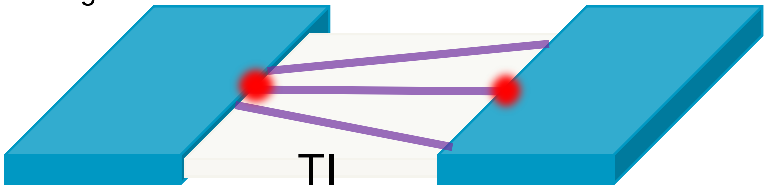
Strong evidence (Würzburg)



2D surface states of 3D topological insulators

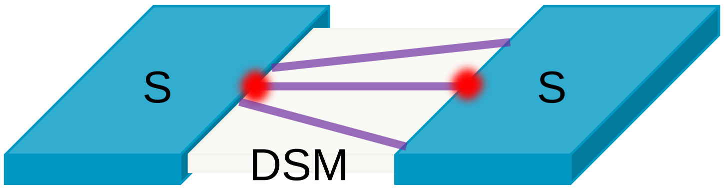
(Bi_2Se_3, Bi_2Te_3, $Bi_1Sb_1Te_1Se_2$)

First signatures

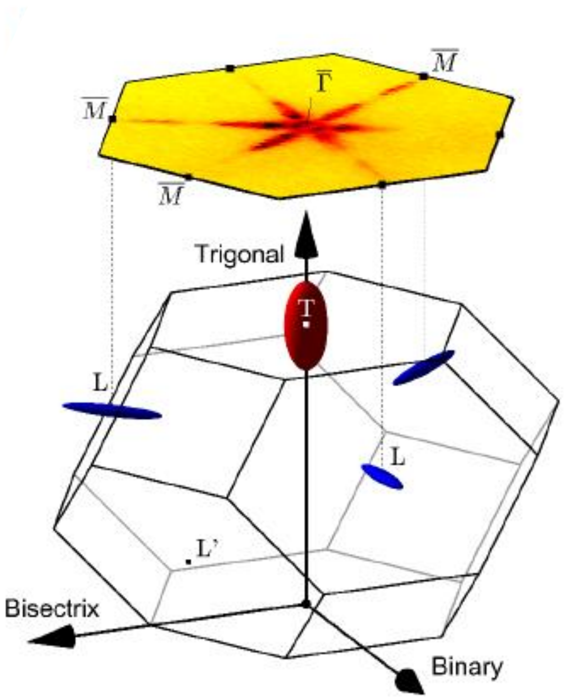


3D bulk states (Dirac/Weyl semimetals)

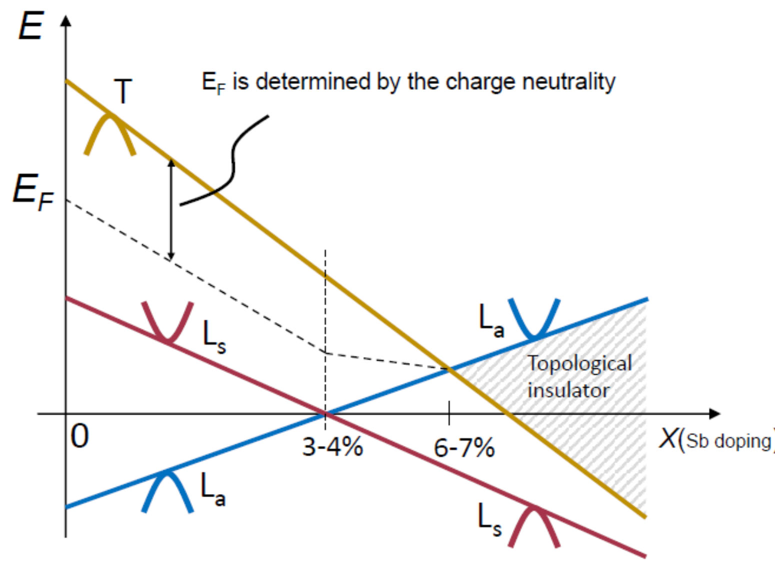
This talk

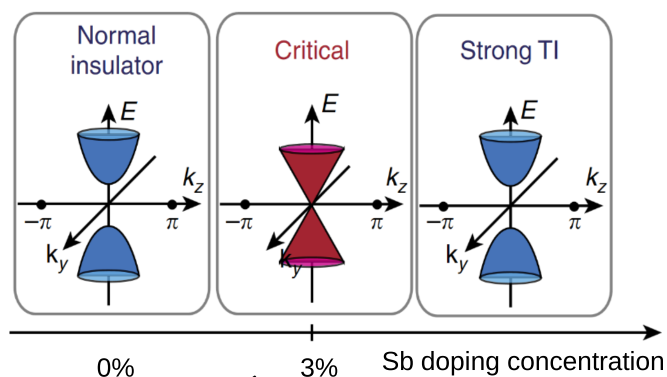


3D Dirac semimetal $Bi_{1-x}Sb_x$



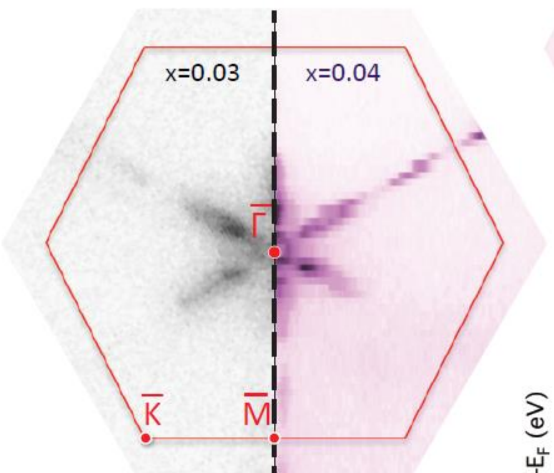
“3D graphene”

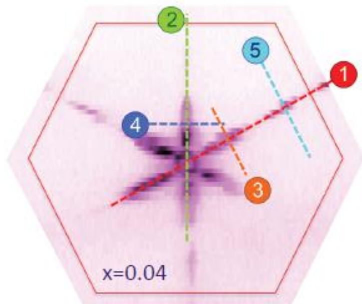


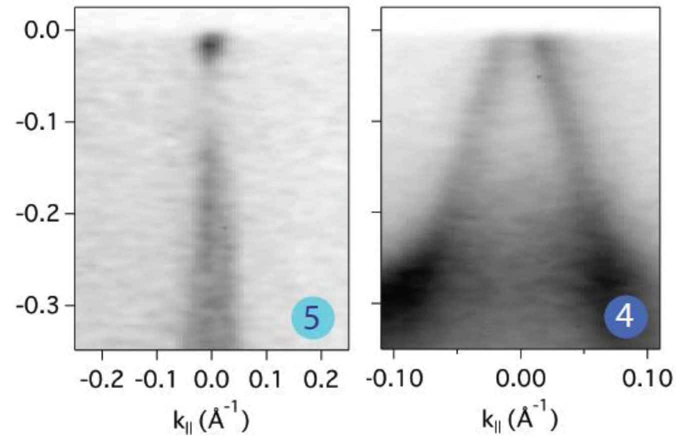


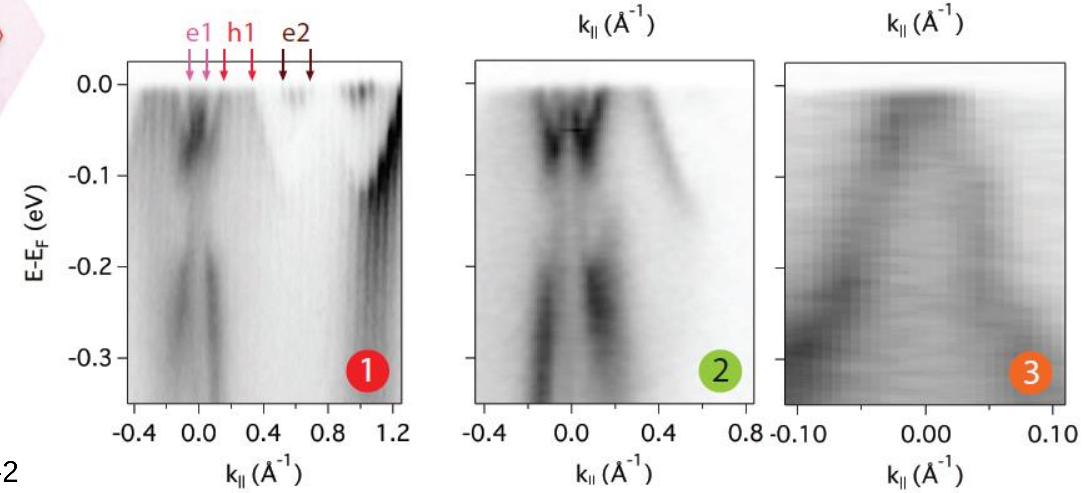
Surface (111) of $Bi_{1-x}Sb_x$

Angle resolved photoemission spectroscopy (ARPES):



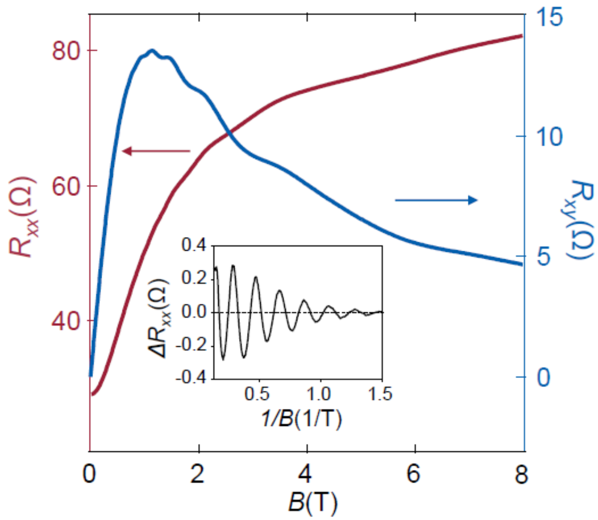


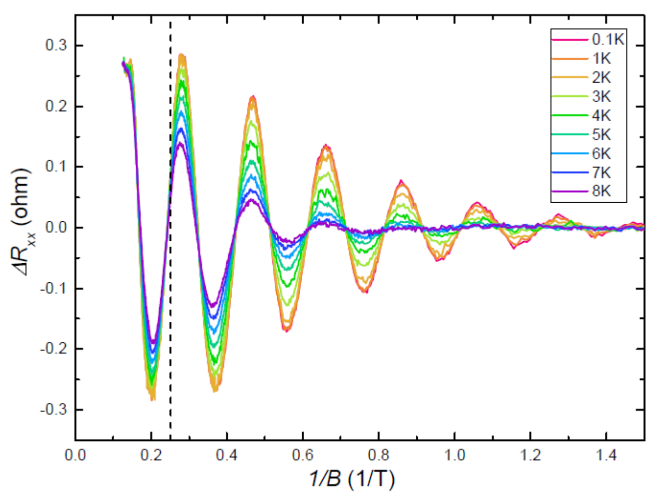


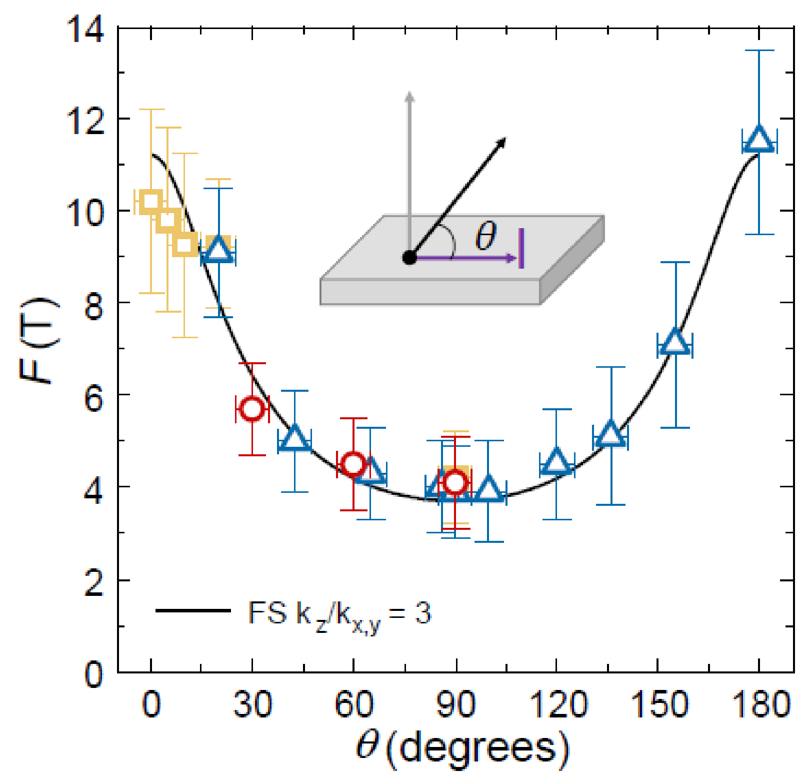


electrons: 1-2 x 10^{12} cm^{-2}
holes: 1-2 x 10^{12} cm^{-2}

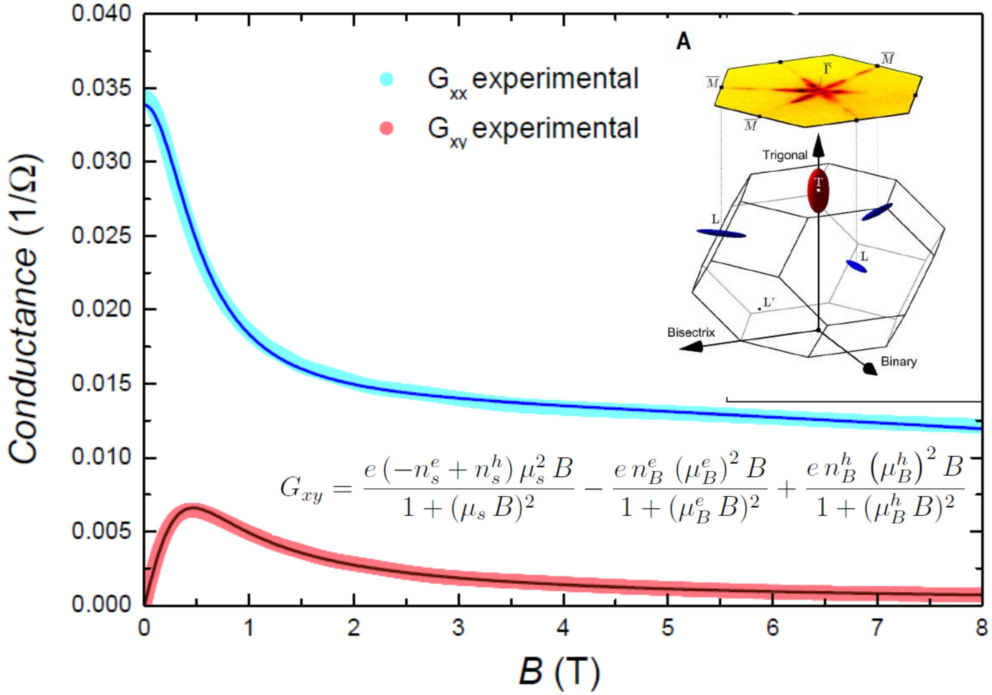
Quantum oscillations of bulk holes







Multiband magnetotransport

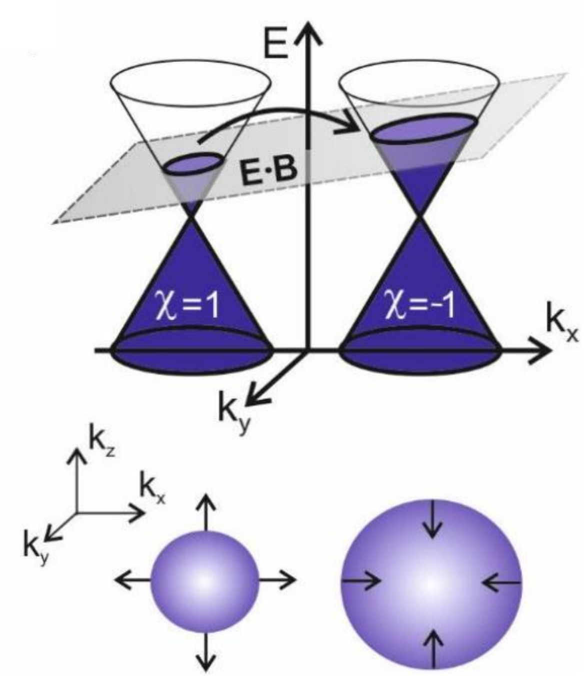


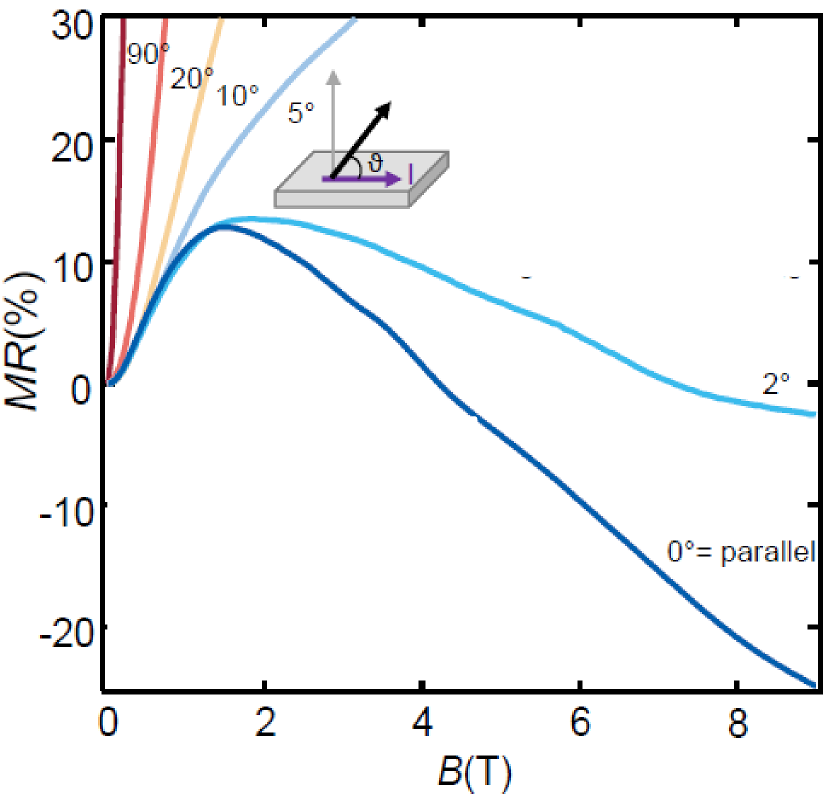
Electrons in the bulk Dirac cone: $0.2 \times 10^{17}\ \mathrm{cm}^{-3}$

$$E_F = \hbar\,(\pi^2 n_e v_1 v_2^2)^{1/3} = 16\ \mathrm{meV}$$

Chiral anomaly in $Bi_{1-x}Sb_x$

Polarization of chirality:



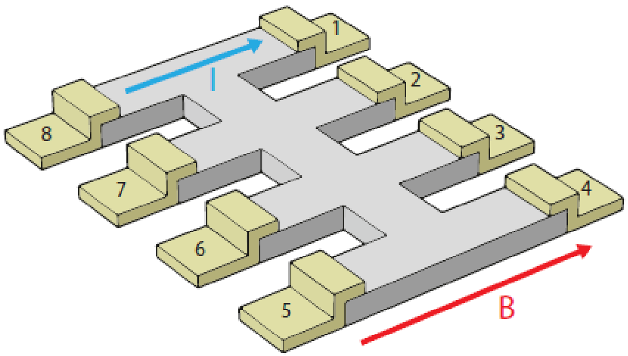


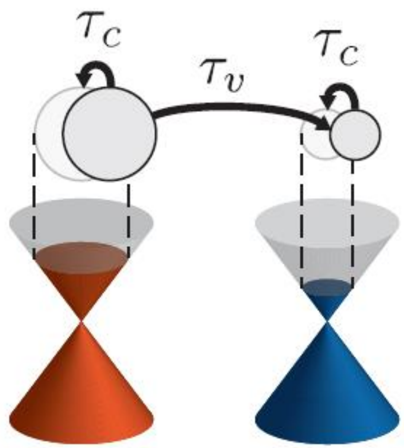
Analogy pion decay:

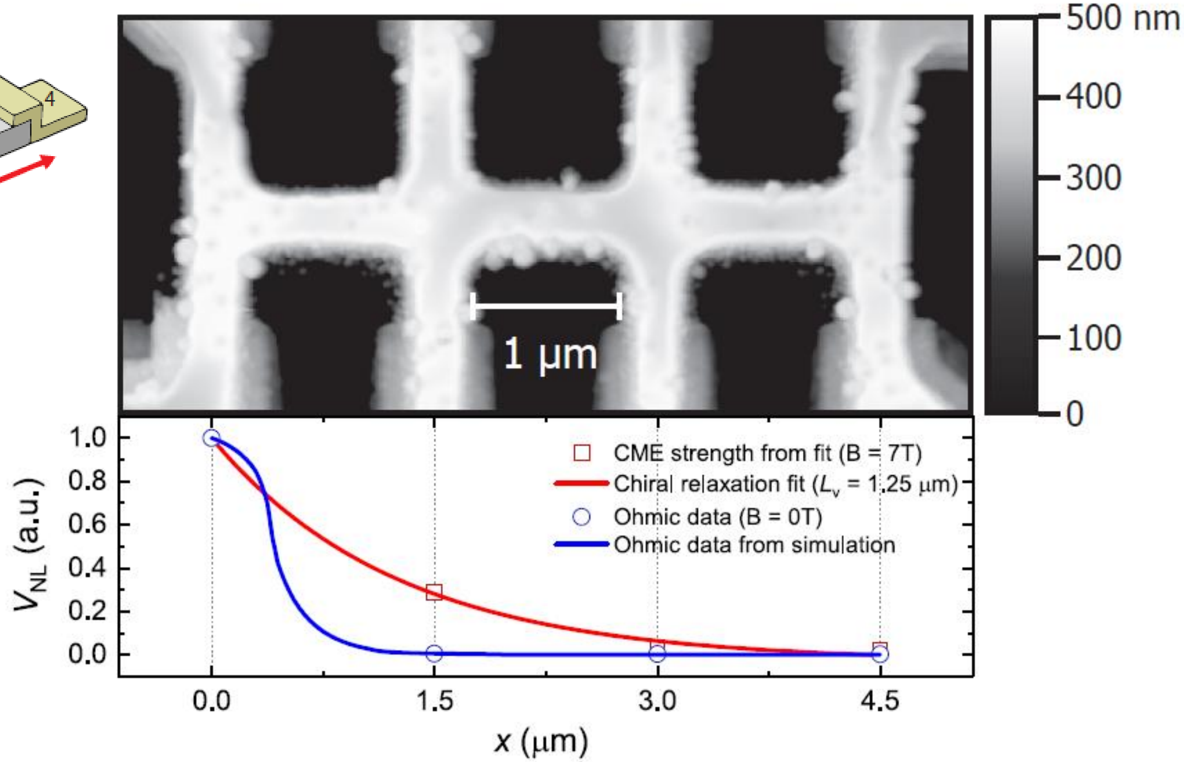
Negative longitudinal magnetoresistance (LMR)

3%✓ 4%✗

Monopole diffusion



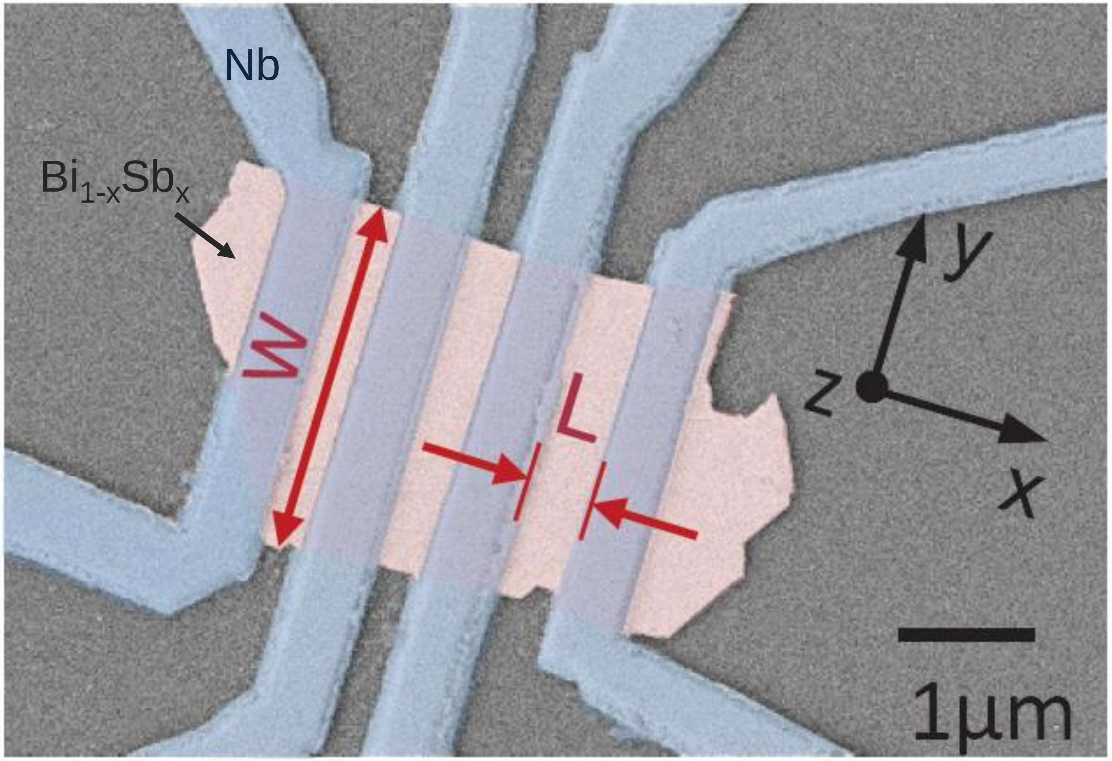




$$\frac{\partial \rho_\pm}{\partial t} = f(\Omega_{\mathbf{k}}) \frac{e^2}{4\pi^2\hbar^2} \mathbf{E} \cdot \mathbf{B}$$

Phys. Rev. B **99**, 085124 (2019)

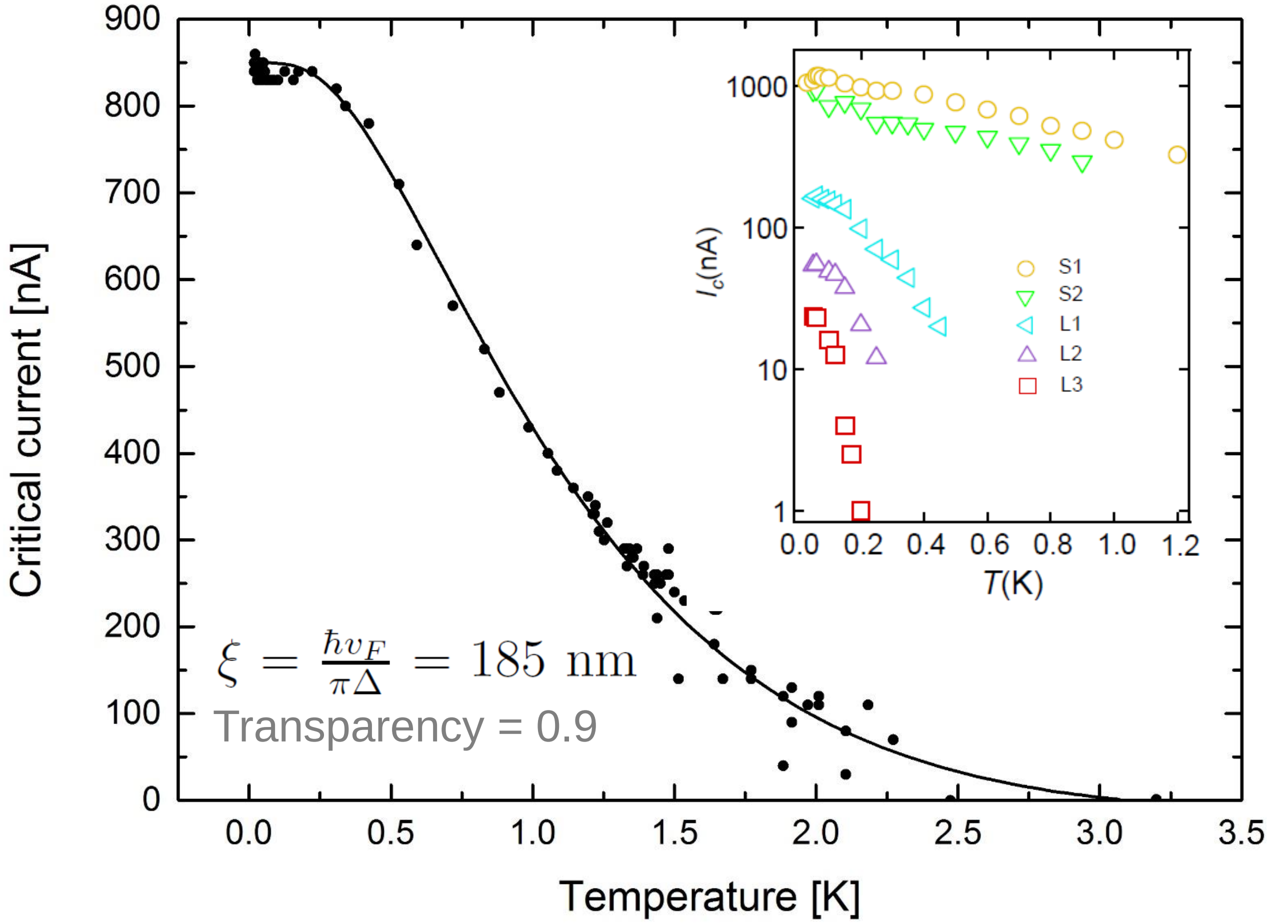
$Bi_{1-x}Sb_x$ Josephson junctions



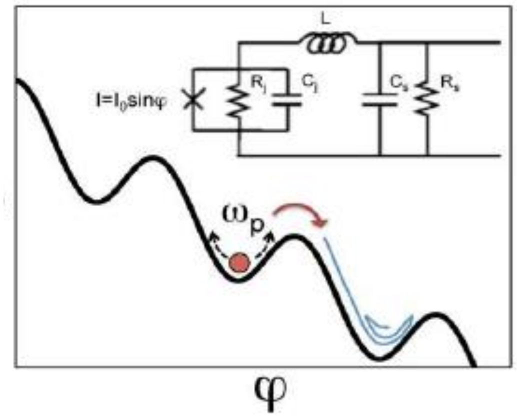
Nature Mater. **17**, 875 (2018)

$Bi_{1-x}Sb_x$ Josephson junctions, x=0.03

Ballistic 500 nm Josephson junctions:

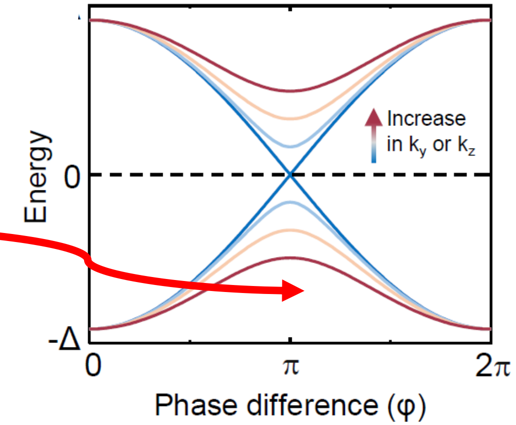


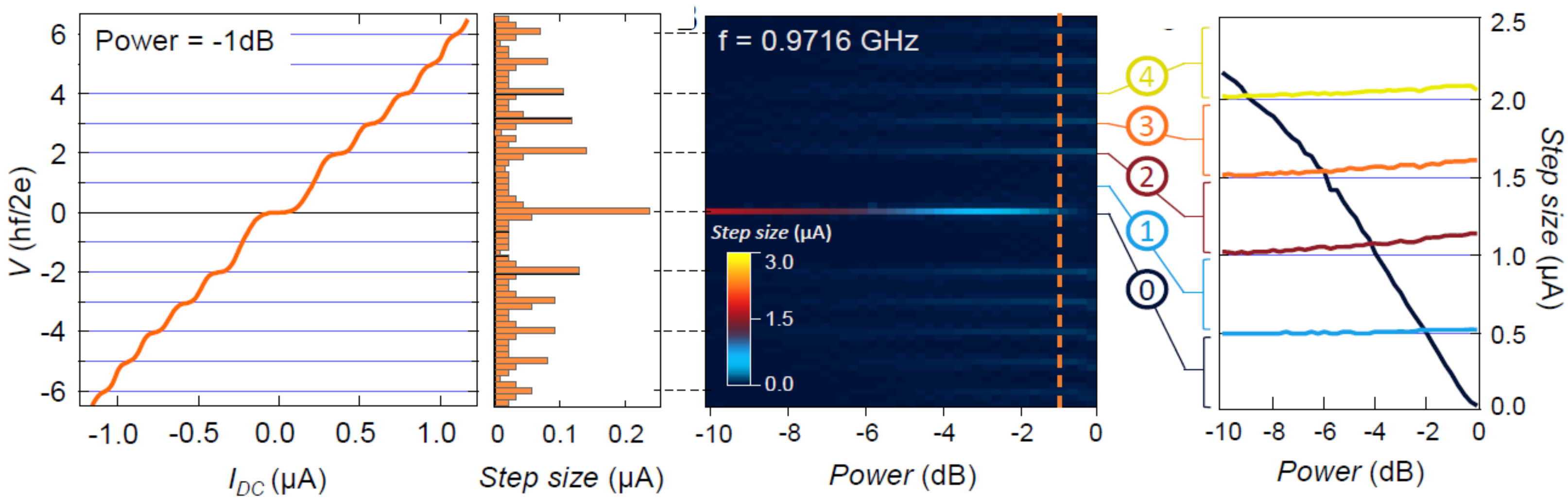
Observation of 4π-periodic supercurrent



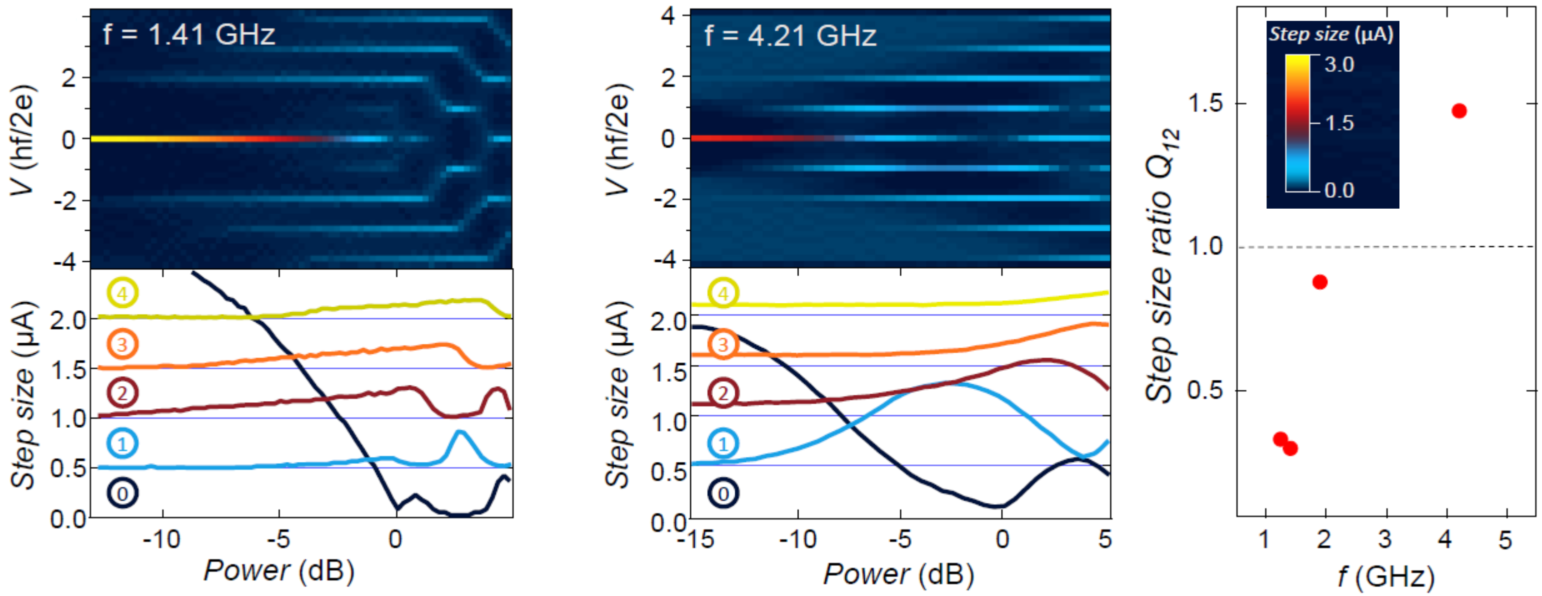
Microwave irradiation:

$$n\frac{h}{2e}\nu$$





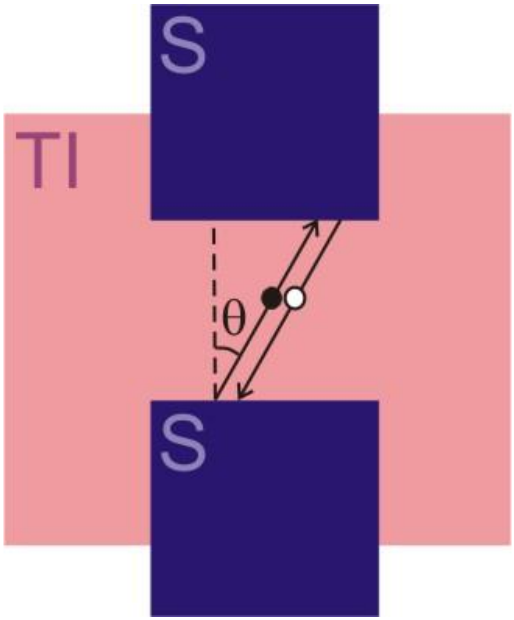
Recovery of 2π-periodicity

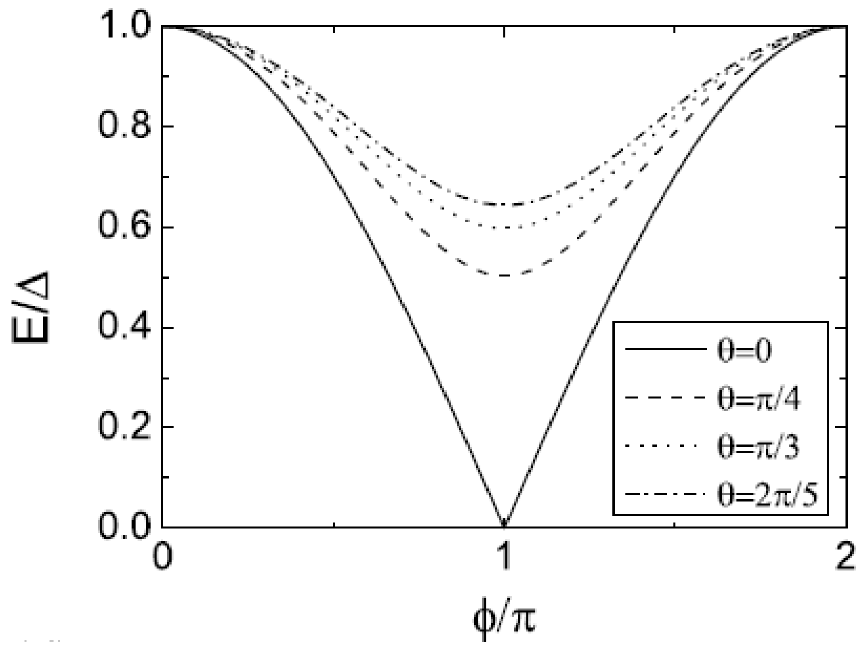


$$f_c = \frac{2e}{h} R_N I_c^{4\pi} \qquad I_c^{4\pi} = 0.2\ \mu\text{A}$$

From the critical frequency we obtain: $I_{4\pi}$ > 20% of I_c

Non-perpendicular trajectories



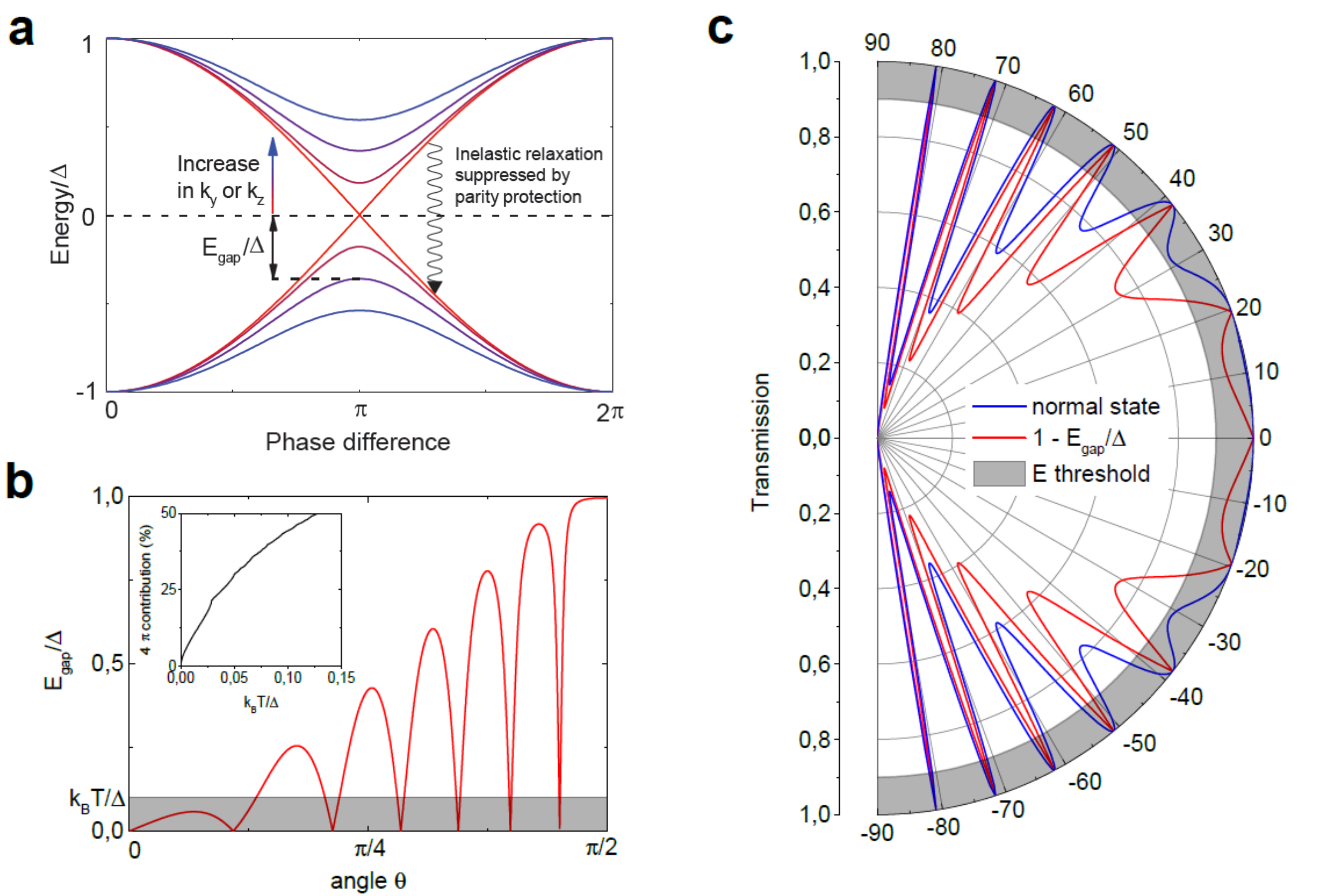


Towards single channel:

1. Quantization of tranverse momentum
2. Including a magnetic layer

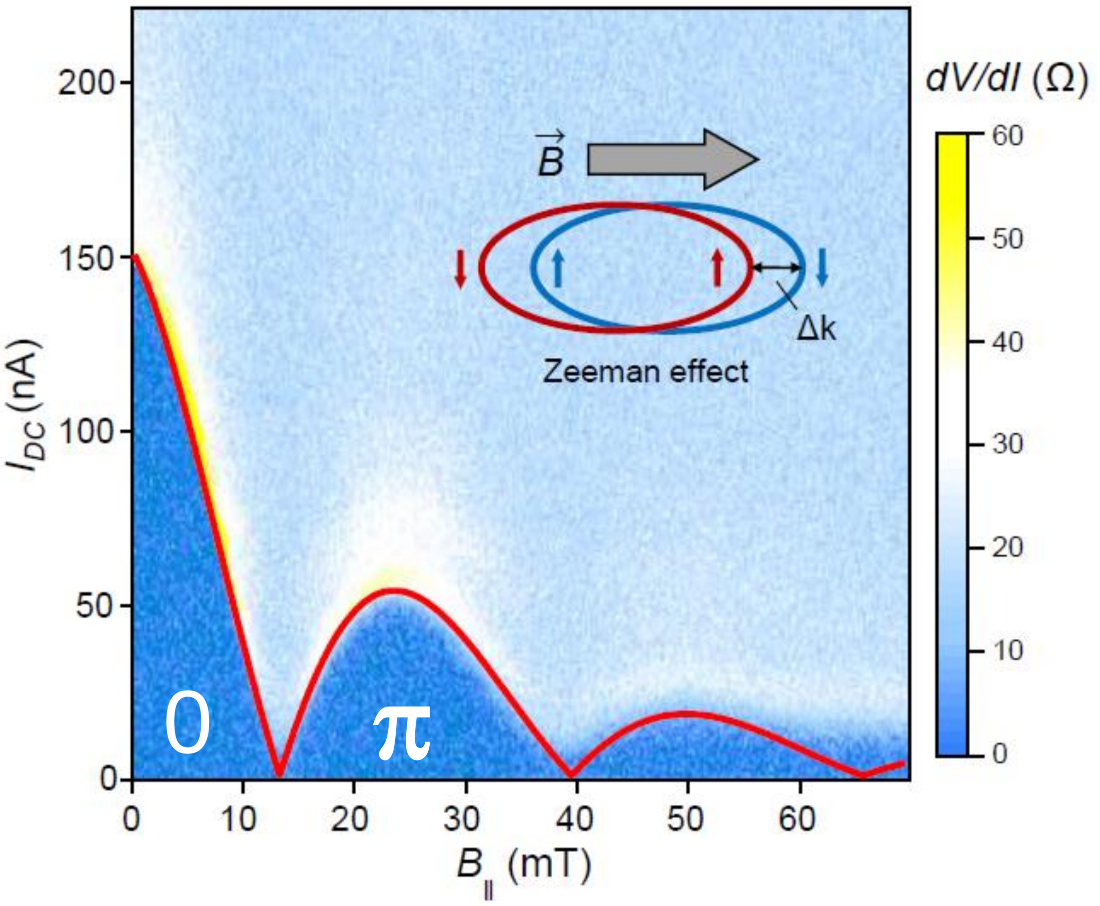
M. Snelder, M. Veldhorst, A.A. Golubov, A. Brinkman, Phys. Rev. B **87**, 104507 (2013)

‘Majorana’ percentage

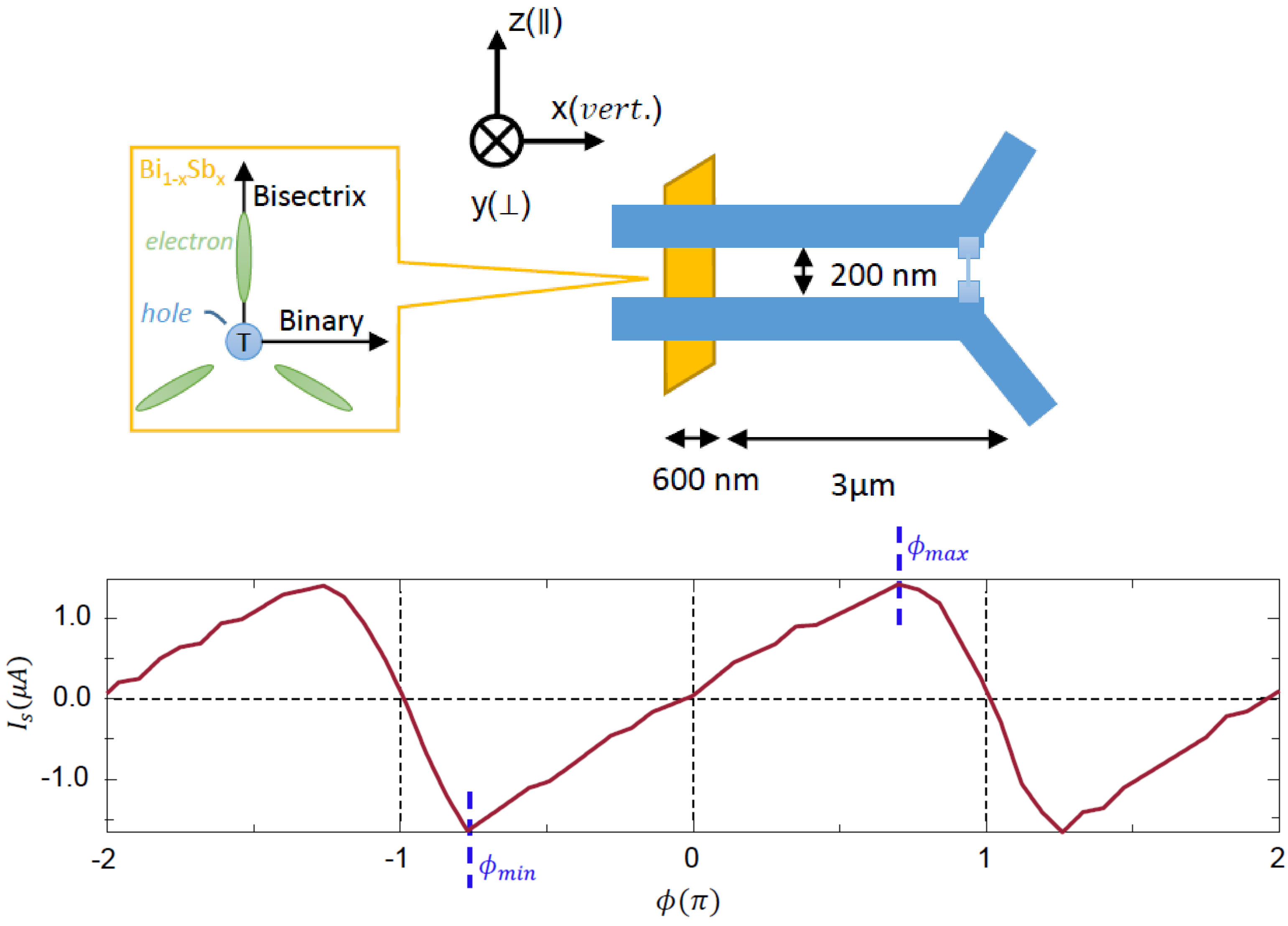


Giant Zeeman effect in Dirac cone

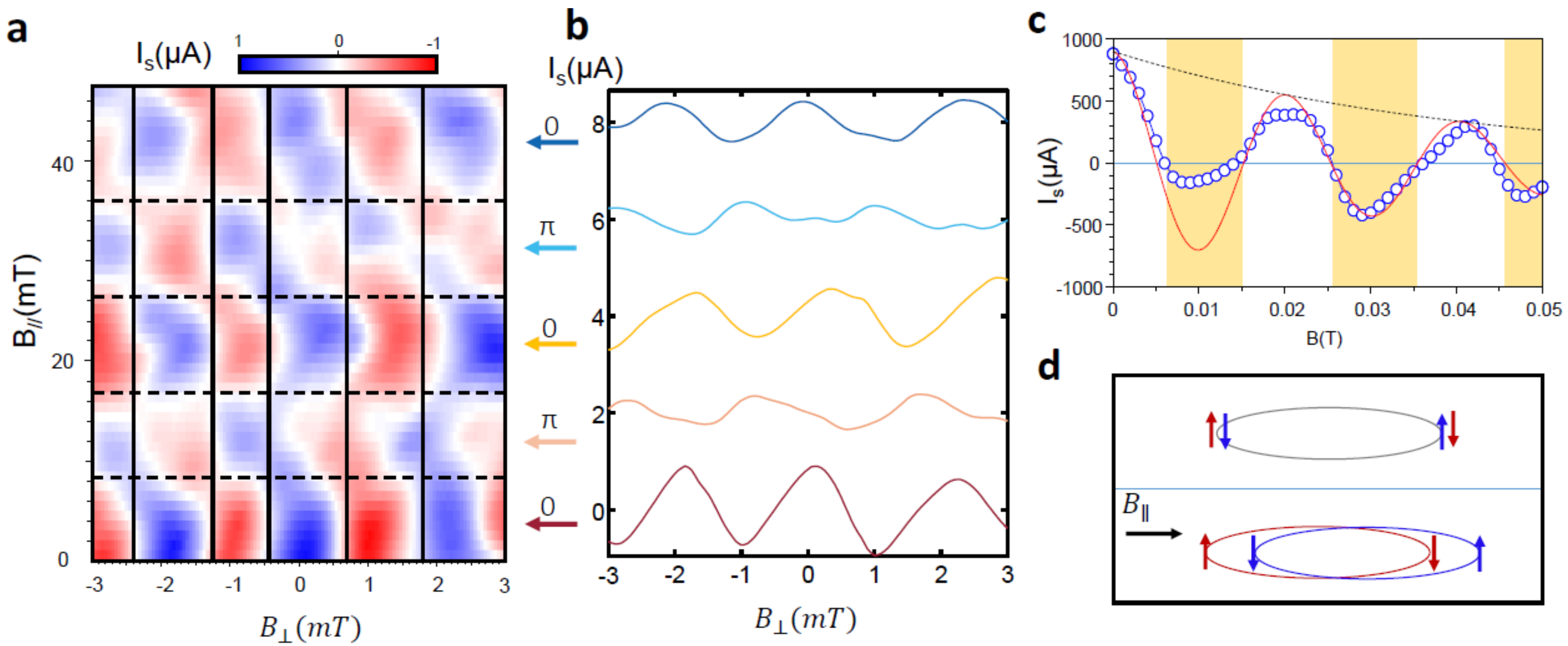
$$\Delta k_x = \frac{g\mu_B B_x}{\hbar v_F}$$ with g = 1000



Asymmetric SQUID for current-phase relation



0 – pi transitions

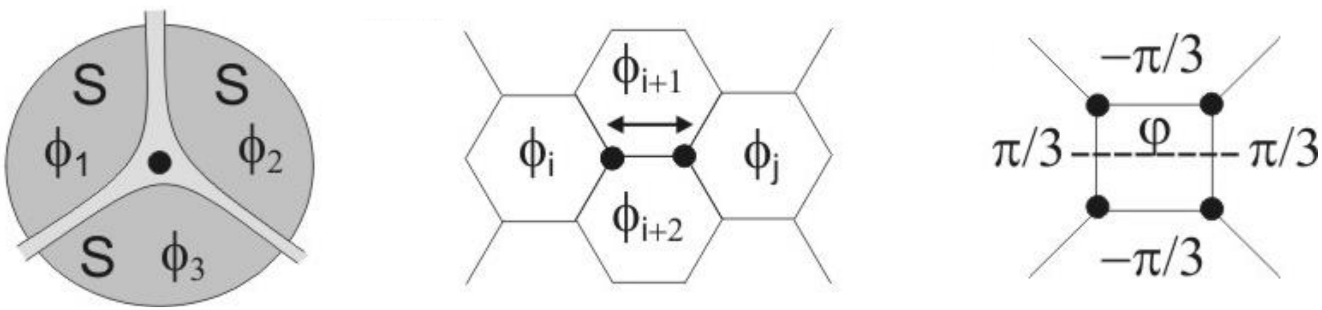


Phys. Rev. Lett. **123**, 026802 (2019)

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), November 2019.
Invited presentation 3-EO-TS-02l given at EUCAS, 1 – 5 September 2019, Glasgow, UK.

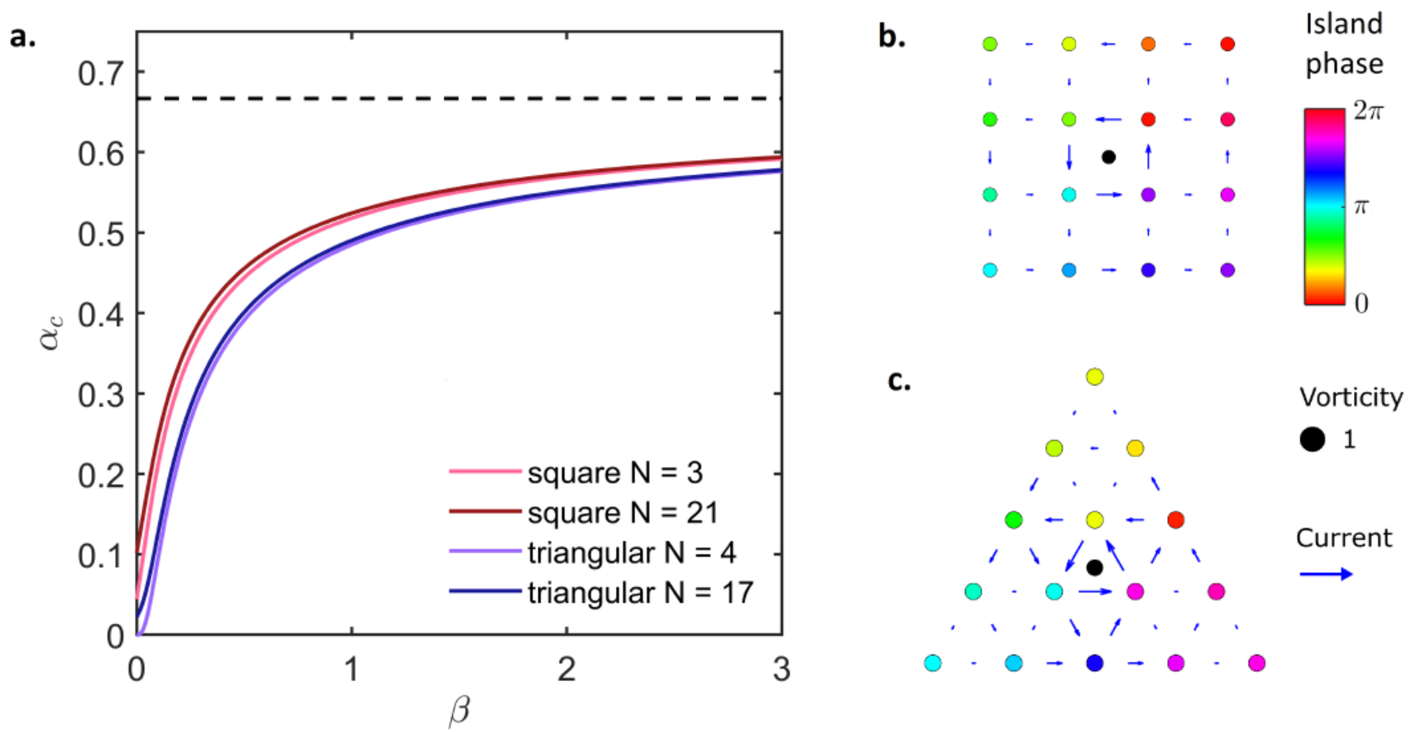
Conclusion and outlook

- Josephson supercurrent observed in several topological Josephson junctions
- Largest Majorana signal in the 3D Dirac semimetal
- Thin films & gating needed



IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), November 2019.
Invited presentation 3-EO-TS-02l given at EUCAS, 1 – 5 September 2019, Glasgow, UK.

Outlook: Majorana vortex lattice

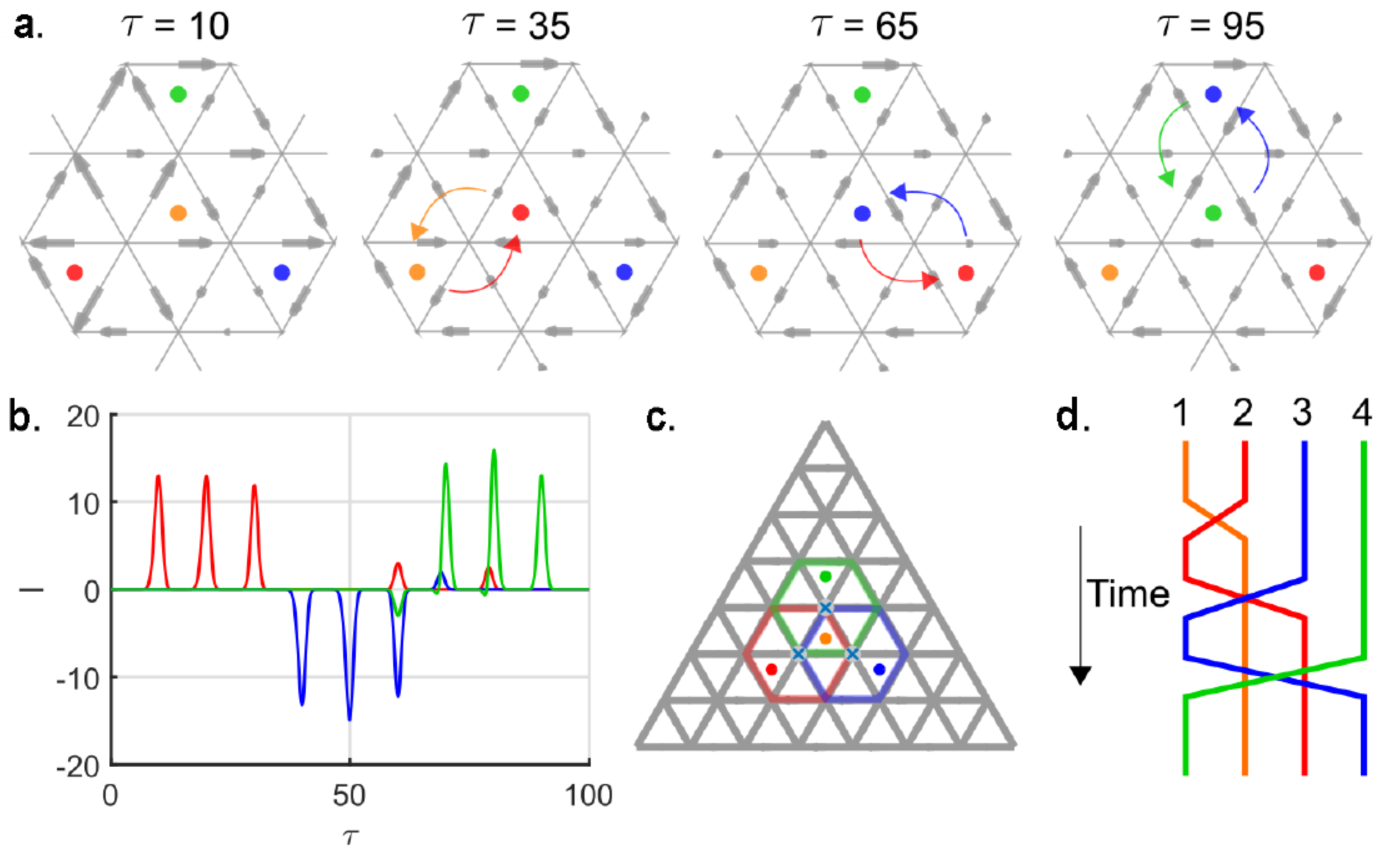


$$\alpha = I_c^{4\pi}/(I_c^{2\pi} + I_c^{4\pi})$$

β = dimensionless self inductance of the loop

Outlook: Majorana vortex lattice

Using ***local current pulses*** instead of flux biasing



Compatible with GHz rapid single flux quantum (RSFQ) technology?

Outlook: Majorana vortex lattice

Using ***global*** current pulses and trap sites